sustainability

MDPI

Article

Challenges and Adaptive Measures for U.S. Municipal Solid Waste Management Systems during the COVID-19 Pandemic

Ana Daniela Pinto, Hiba Jalloul, Navid Nickdoost, Fehintola Sanusi, Juyeong Choi * and Tarek Abichou

Department of Civil and Environmental Engineering, FAMU-FSU College of Engineering, Tallahassee, FL 32310, USA; adp15d@my.fsu.edu (A.D.P.); hj20bf@my.fsu.edu (H.J.); nn19b@my.fsu.edu (N.N.); fbs16@my.fsu.edu (F.S.); abichou@eng.famu.fsu.edu (T.A.)

* Correspondence: jchoi@eng.famu.fsu.edu

Abstract: The coronavirus pandemic has resulted in major disruptions in the way municipal solid waste management systems (MSWMSs) operate due to substantial distortions in waste generation trends, along with a variety of significant operational and managerial challenges. As critical infrastructure, MSWMSs have endeavored to adapt in response to such unprecedented stresses in order to maintain their operations during the pandemic. The challenges and their relevant adaptive measures, however, have varied with the progression of the pandemic across different MSWMSs. Currently, there is a limited understanding of such time-bound and system-specific phenomena, which impedes timely and effective adaptation. This study aims to fill this knowledge gap by performing a detailed and documented investigation of the longitudinal impact of the coronavirus pandemic on different MSWMSs across the United States, along with its evolution over time, using collected qualitative and quantitative data (i.e., monthly interviews with waste management personnel, online news media, and waste tonnages). This study also develops a relational database system to facilitate the systematic recording and monitoring of the pandemic's impact on MSWMSs, as well as guide the implementation of different adaptation strategies based on distinct systems' characteristics. Findings of this study will help solid waste decision-makers better understand the current pandemic, along with serving as a knowledge base for future pandemic scenarios towards more resilient MSWMSs.

Keywords: adaptive measures; challenges; COVID-19; pandemic; qualitative research; solid waste management

Citation: Pinto, A.D.; Jalloul, H.; Nickdoost, N.; Sanusi, F.; Choi, J.; Abichou, T. Challenges and Adaptive Measures for U.S. Municipal Solid Waste Management Systems during the COVID-19 Pandemic. *Sustainability* **2022**, *14*, 4834. https://doi.org/10.3390/su14084834

Academic Editors: Marco Ragazzi and Elena Magaril

Received: 23 March 2022
Accepted: 15 April 2022
Published: 18 April 2022

1. Introduction

The novel coronavirus, known as COVID-19, has triggered unparalleled disruptions to global health, the world economy, and every aspect of our social lives. According to the World Health Organization (WHO), over 286 million confirmed cases and more than 5.4 million deaths were recorded worldwide by the end of 2021 [1]. As the speed and severity of the COVID-19 outbreak increased, and with all the enacted global measures, no sector has remained unimpacted, one of which is waste management. The substantial increase in medical waste [2,3], caused by increasing infection rates, has exerted immense stress on the waste management sector, which is not typically designed for major disruptions such as the COVID-19 pandemic. These repercussions, accompanied by lifestyle changes due to limitations placed on mobility, the commercial sector, and manufacturing activities, among others, have become significant complications with the management of municipal solid waste (MSW).

Municipal solid waste management systems (MSWMSs) meet one of the basic needs of residents, which is the timely and safe collection, treatment, and management of their generated waste [4]. In terms of environmental and economic benefits, MSWMSs play an important role in promoting the sustainable management of materials, stimulating the economy, and creating jobs by reusing and recycling materials that would otherwise be sent

to landfills [5]. From a public health perspective, whether during a pandemic or during 'normal times', MSWMSs are critical for limiting the spread of infectious diseases [6,7] and environmental pollution [8–10], through the proper management of hazardous waste and minimizing waste contamination. With their many roles, MSWMSs are essential infrastructure before, during, and after major disruptive events. If such essential infrastructure fails, the buildup of waste can lead to a sanitary and environmental crisis, economic repercussions, social frustrations, and distress [4,11,12].

Since the beginning of the COVID-19 pandemic, MSWMSs have been significantly impacted due to severe changes in the generation rates of different waste streams, intricate operating conditions amid fears of virus transmission, and restrictive new measures and regulations, among others. During lockdowns imposed as a result of the pandemic, China experienced a 30% decrease in the quantity of MSW [13], while a considerable increase in domestic waste was reported in the United Kingdom [14]. In the United States and at the early stages of the pandemic, the Solid Waste Association of North America (SWANA) reported a 20% increase in the volume of residential waste nationally, with the increase surpassing 30% in some cities [15]. New York City, for example, experienced an increase in residential waste ranging between 5 and 30%, along with a decrease in commercial and industrial waste reaching 50% [16]. With regards to recycling, the demand for recycled plastics decreased by 30 to 40% in China and Southeast Asia amid the sudden drop in the price of oil and revocations of orders by international manufacturers [17]. In the United States during the early months of the pandemic, Ohio, South Carolina, Arizona, and New York reported a 45% increase in recycling operations as compared to 2019 [18], whereas Oregon, California, and Michigan experienced a 45% drop in received/collected recyclables as compared to the same period in 2019 [19].

As challenges emerged, so did the mitigation strategies adopted by different MSWMSs to maintain their functionality. To reduce the risk of COVID-19 transmission, some municipalities in the United States suspended their recycling services [20]. Whereas European countries such as France, Italy, the United Kingdom, and Spain continued their recycling operations, considering them essential [17], while banning the recycling of waste from households containing residents with COVID-19 confirmed cases [21]. Some countries, such as Austria, advised their citizens to reduce the amount of their generated waste and appropriately sort it [22]. In light of the increase in residential waste, the City of York, Pennsylvania, suspended the collection of yard waste and diverted those resources to the collection of residential solid waste [23].

Responding to the unprecedented changes to the status quo, a number of studies have been published investigating different aspects of the pandemic's impact on solid waste management. During the early stages of the pandemic, when waste management data were still not sufficiently available, researchers [24,25] started questioning and hypothesizing how the pandemic will impact the generation, composition, and management of solid waste. Once public waste management data started emerging, studies focused on identifying the main critical challenges faced by waste management systems worldwide while also proposing some mitigation strategies. Most of these studies discussed solid waste in general (i.e., including biomedical, industrial, and MSW) [26–33], with very few particularly focusing on MSW [4,34–36]. Further, they all examined the problem from a macro-level perspective, studying the general impact of the COVID-19 pandemic on waste management worldwide without investigating how this impact has varied across different MSWMSs (i.e., in different regions and urban versus rural settings), facing distinct challenges and responding with unique adaptive measures. In addition, none of the existing studies takes into consideration the impact of the progression of the pandemic on these challenges and adaptive measures. Among the reviewed studies, only Van Fan et al. [28] looked at how the quantities of some of the generated waste streams change over time, but such analysis was limited only to the first several months of the pandemic (i.e., up to June 2020) and was not applied to the rest of the identified waste management challenges. As such, there remains

a limited understanding of how the current pandemic has impacted MSWMSs, which in turn impedes timely and effective response and adaptation.

Further, the data relevant to the impact of a pandemic on MSWMSs and their corresponding responses have a perishable nature; any managerial and operational challenges will be eventually resolved, and systems will resume their normal operation when a pandemic is over. Unlike disasters, evidence of a pandemic's impact is retained within the memories of waste management operators instead of being in physical, visible objects (e.g., damaged infrastructure) that may remain available until restoration/reconstruction. As such, it is important to properly capture and document such ephemeral data in a timely manner.

This study aims to fill the current knowledge gaps and needs by performing a novel and documented micro-level investigation of the pandemic's impact on MSWMSs. Specifically, the objectives of this study are to identify, categorize, and analyze the challenges faced, and adaptive measures implemented by MSWMSs, while taking into consideration each system's unique entities, characteristics, and conditions surrounding its response, as well as the factor of time. To achieve these objectives, a systematic approach was followed to collect and analyze different forms of data, corresponding to different types of MSWMSs: qualitative data collected through monthly interviews and online news media content analysis, along with quantitative data in the form of monthly waste tonnages. Findings from this study led to the establishment of a documented knowledge base of the time-bound pandemic's impacts and corresponding responses associated with different MSWMSs' characteristics. Such knowledge base augments our understanding of the current pandemic and aims to guide researchers and waste management decision-makers in adopting the most suitable adaptation strategies in future pandemics for more resilient MSWMSs.

2. Methodology

This study collects data from nine MSWMSs, with diverse levels of urbanization, across three of the U.S. states most impacted by the pandemic, namely Florida, New York, and California. Over a ten-month period, data were systematically collected by means of three distinct data collection methods: monthly interviews with waste management personnel, waste tonnage data analysis, and online news media content analysis (Figure 1). These three complementary methods were utilized to ensure that we captured and documented all relevant information about the challenges and adaptation processes of MSWMSs during the pandemic in a comprehensive and timely manner.

2.1. Monthly Interviews

Interviews were performed to understand waste management decision-makers' varying subjective experiences, behaviors, and opinions over time (i.e., as the primary source of qualitative data). This was done to primarily understand the challenges MSWMSs were facing during the pandemic, their implemented adaptation strategies, and how those two changed with time as the systems' regional contexts evolved. Specifically, semi-structured interviews were conducted using an interview guide, in which topics were drawn from the literature based on the study's objectives, along with having open-ended questions that allowed participants to introduce new ideas to the study [37]. In order to identify and trace emerging MSWMSs' managerial and operational challenges with their respective adaptive measures, the interview guide divided the questions into seven different post-pandemic waste challenge categories: collection, recycling, health, business, construction and demolition (C&D) waste, and waste-to-energy (WTE). During each conducted interview, all seven categories were introduced, and all questions pertaining to each category were asked to the participating MSWMSs' representatives.

Interviewed waste management personnel were initially identified through professional associations (e.g., SWANA) and the authors' professional networks and, subsequently, invited to participate in this study through email. Considering the geographical distribution of the studied MSWMSs across different states (i.e., Florida, New York, and Cal-

ifornia) and COVID-19 travel restrictions, all monthly interviews were conducted via video conferencing and telephone. Each interview was digitally recorded and later transcribed into a report for accuracy. A survey spreadsheet was created and sent to the MSWMSs' participant following each monthly interview as part of the follow-up meetings plan to confirm the findings.

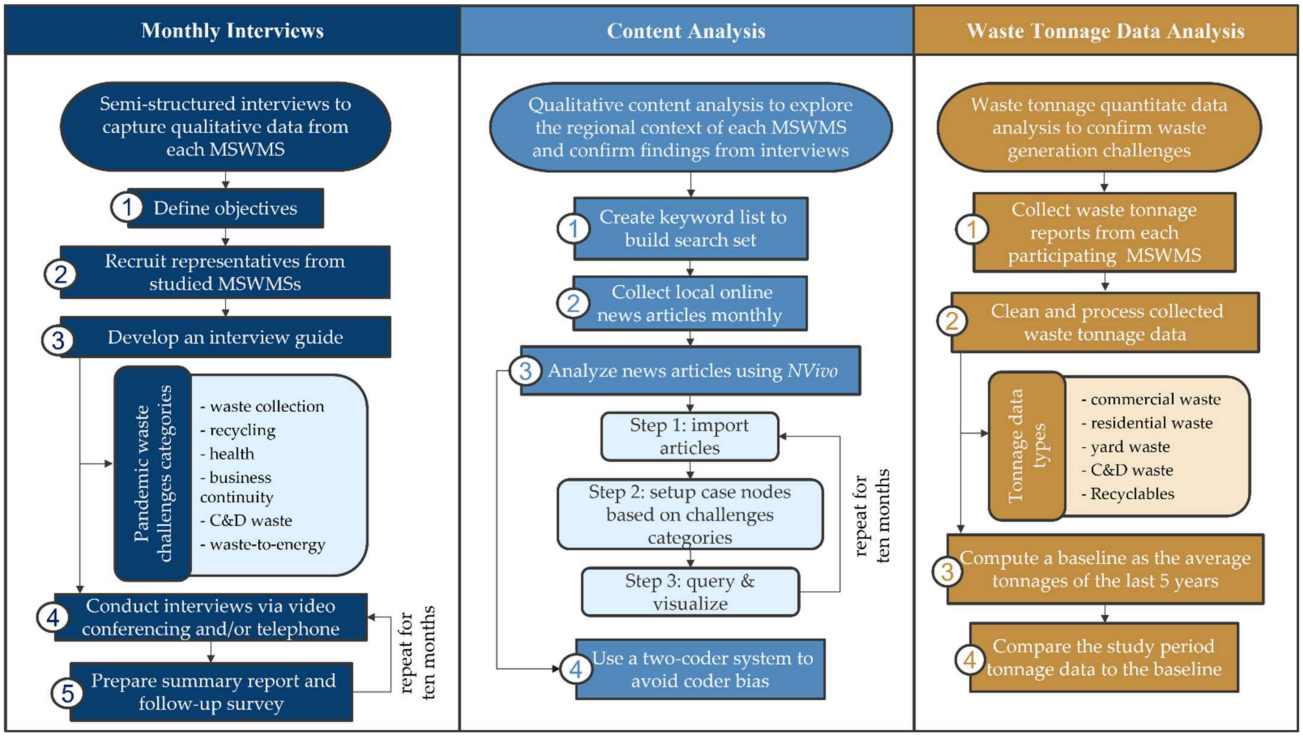

Figure 1. Data collection methods.

2.2. Content Analysis

Complementary to the monthly interviews, COVID-19- and waste-related local news articles were analyzed in this study. This supplementary qualitative data collection approach was used to (i) improve the robustness of the findings from the monthly interviews, (ii) capture the information otherwise missing if the study only relies on the subjective opinions of the interviewed MSWMS entities, and (iii) augment our understanding of the regional context that may affect the operation of MSWMSs and their adaptation strategies. Specifically, online local (i.e., state- and county-level) news articles corresponding to studied MSWMSs were collected monthly over the study period. A list of keywords was used to build the search set, including "waste", "recycling", "landfill," "contamination", "COVID-19", "garbage", "infrastructure", and "pandemic", which helped narrow down the search scope.

Following the collection of all relevant news articles, their content was analyzed. Content analysis has been widely used to systematically reduce the content of unstructured data and analyze its context to identify themes and extract meaningful interpretations [38]. It was conducted in this study using the qualitative data analysis software NVivo. Collected articles were first imported into the software, and then nodes that contain references about a specific topic-related material were coded. In an effort to avoid coder bias and increase the reliability of the coded data, this study used a two-coder system [39]. In other words, each analyzed text was coded by two human coders, and results were thereafter compared for reliability using two measures of the degree of agreement: percentage agreement and Kappa coefficient (i.e., a statistical measure that considers the amount of agreement that could be expected to occur through chance). The resulting average percentage agreement and

average Kappa coefficient were 99.64 and 0.89, respectively, indicating a good agreement according to Landis and Koch [40].

To analyze the findings from the content analysis, word frequency queries were utilized. Specifically, they were used to quantitatively understand major events related to waste management by looking at the most frequently used words in the analyzed text. Figure 2 shows an example illustration of the data visualization used to show the results.

Figure 2. Word cloud format showing the results of the word frequency queries.

2.3. Waste Tonnage Data Analysis

In addition to the collected qualitative information, this study examined quantitative data about the volume and composition of the waste generated in the studied MSWMSs. Waste tonnage data were retrieved by collecting monthly waste and recycling reports corresponding to the study period, along with reports reflecting waste generation trends during previous years. With each studied MSWMS having a unique data reporting system, collected data were first cleaned and processed (i.e., waste tonnages for all common waste streams across the nine studied MSWMSs were computed monthly). Subsequently, the data were analyzed by comparing the waste tonnages of the study period to a baseline taken as the average waste tonnages of the last five years preceding the pandemic. Such comparison enabled the investigation of emerging MSWMSs' waste generation challenges (e.g., an increase in residential volume, a decrease in commercial volume, and an increase in recycling contamination), along with confirming some of the findings from the monthly interviews and content analysis.

3. Regional Contexts of Studied MSWMSs by State

Before investigating the impact of the COVID-19 pandemic on the studied MSWMSs, it is important to understand the regional context that may impact the challenges faced, and adaptive measures implemented by each MSWMS. As such, this section highlights some significant unique characteristics of the studied MSWMSs at the state level (i.e., Florida, New York, and California), along with the enacted ordinances during different stages of the pandemic.

Each state has distinctive pre- and in-pandemic characteristics distinguishing the structure of their MSWMSs. To be more specific, according to the Florida Department of Environmental Protection, Florida has the largest capacity to burn MSW with eleven operating WTE plants [41]. Florida uses WTE as its primary waste disposal method because it does not only decrease the volume of waste going to landfills but also allows for energy recovery from the waste combustion process. In contrast, in January 2022, a bill was passed

in California to discourage the diversion of waste to incineration facilities [42]. To reduce its dependence on landfills, California has taken a different approach in recent years by mainly pursuing waste recycling and reducing other sources of solid waste. Likewise, the state of New York has been focusing more on increasing waste recycling and composting. Over the years, it has implemented several bans and laws to accomplish this goal. For example, at the beginning of 2020, New York adopted the Go Foam Free ban and the Bag Waste Reduction Law to decrease single-use foam containers and plastic bags [43].

Further, during the pandemic, new policies and regulations were implemented in each of Florida, California, and New York to limit the spread of COVID-19, ultimately affecting the waste generation and how studied MSWMSs in these states operate. For instance, Florida ordered all restaurants and bars to switch to take-out and delivery only in March, issued a statewide stay-at-home order in April, and started to gradually reopen and return to normal operations in May [44]. These ordinances led to a significant increase in the volume of residential waste during the early months of the pandemic. California has implemented even stricter COVID-19-related measures compared to Florida. Such aggressive measures caused California to reopen local businesses at a much later stage compared to Florida and insist on re-implementing the stay-at-home restrictions if intensive care unit capacity falls below 15% [45]. California also mandated face coverings in public indoors and outdoors at the beginning of the pandemic and kept such mask requirements throughout the study period even when other states started lifting them [45]. These measures have altered residential and commercial waste generation trends, along with impacting the daily operations of waste management personnel and MSWMSs. The state of New York also took aggressive COVID-19-related measures and enacted some policy changes. Its guidelines regarding the reopening of businesses in small capacity increments lasted until the end of our study period (i.e., February 2021). Its statewide mask requirement was extended through the beginning of 2022 regardless of vaccination status in indoor public settings [46]. Further, reusable grocery bags were temporarily suspended in New York, and the bottle bill enforcement was relaxed, all of which led to an increase in single-use plastic packaging entering the waste stream [47,48].

4. The Longitudinal Impact of the Pandemic on Waste Facilities

After gaining an understanding of the regional contexts of the studied nine MSWMSs across Florida, California, and New York, we investigated the longitudinal impact of the COVID-19 pandemic on these MSWMSs. Specifically, this section reports the identified waste management and operational challenges faced by MSWMSs during the pandemic, along with their implemented adaptive measures. As previously mentioned, these findings were grouped into seven categories: waste collection, waste recycling, health, business, C&D waste, and WTE challenges. In order to investigate how challenges and adaptive measures in each category change over time, the study period was divided into four quarters: March to May of 2020, June 2020 to August 2020, September 2020 to November 2020, and December 2020 to February 2021. Findings were reported for each quarter by means of frequency analysis. In other words, for each category, the number of systems experiencing each challenge out of the nine studied MSWMSs is reported for each quarter.

4.1. Waste Collection

Figure 3 depicts changes in the waste collection challenges over the pandemic timeline. All of the reported waste collection challenges emerged during the first quarter of the study period. The challenges that persisted throughout the remaining three quarters are (i) an increase in residential waste volume, (ii) an increase in self-haul services, and (iii) a shortage of personnel due to illness and quarantining.

All of the MSWMSs experienced abrupt changes in their waste streams. For instance, systems experienced an increase in residential waste volume ranging from 5% to 14% with respect to previous years while having a decrease in commercial volume ranging from 7% to 11%. These trends were observed throughout all states, mainly due to changes in statewide

ordinances according to the representatives of participating MSWMSs. Other reasons included the closure of non-essential businesses such as bars and gyms, the switching of restaurants to take-out and delivery only at the beginning of the first quarter, and the issuance of statewide stay-at-home orders. Subsequently, as each state entered phases of reopening starting in May through September 2020, the commercial waste tonnage followed a gradually increasing trend. While the concern about the decrease in commercial waste volume was not reported after the second quarter when local businesses were allowed to reopen, the concern about the increase in residential waste volume persisted throughout the study period, as many people were still working from home and avoiding outdoor public activities amid COVID-19 concerns. Further, specifically during the third and fourth quarters, systems in California and Florida reported that the observed increase in residential waste volume was due to delays in curbside collection services during previous months.

Figure 3. Waste collection challenges affecting MSWMSs throughout the study timeline.

The rise in residential waste volume indirectly impacted other waste streams. Interviews with representatives of participating MSWMSs in Florida revealed that yard waste collection services were partly suspended at the beginning of the first quarter, as resources were prioritized for the collection of increasing volumes of residential waste. The suspension of yard waste collection resulted in said waste significantly accumulating (e.g., one system in Florida reported a 19% increase in yard waste). The rise in the number of unavailable collection workforces due to illness and quarantine further exacerbated challenges in collecting increasing volumes of waste. According to the news media, the main reason behind such a rise was states' reopening, which further increased the exposure to the virus. All reported waste collection challenges brought business challenges into MSWMSs (e.g., a decrease in waste collection revenues and an increase in trash collection costs). These challenges will be further discussed in Section 4.4.

In response to the waste collection challenges faced, studied MSWMSs employed a number of different adaptive measures, as presented in Table 1. To mitigate the impact of the increase in residential waste volume, studied MSWMSs in all states adjusted waste collection routes, modified the allocation of staff, and increased the operational hours. These adaptive measures were easily implemented since most systems own and operate residential waste collection. In one of the Florida MSWMSs, the utilization of rate reserve funds and moving yard waste staff to residential waste collection were used as stricter adaptive measures in response to the challenges related to waste volume changes. Another challenge that affected all participating MSWMSs was the decrease in commercial waste

volume due to the temporary closure of businesses. Even though all MSWMSs experienced this challenge at least once during the study timeline, only MSWMSs in Florida implemented adaptive measures. Similarly, all adaptive measures reported in Table 1 for the remaining waste collection challenges (i.e., increase in self-haul services and increase in yard waste) only pertain to participating MSWMSs in Florida.

Table 1. Summary of adaptation strategies taken for each waste collection challenge.

Challenge Category	Challenge Subcategory	Adaptive Measures (States)
Waste Collection	Decrease in commercial waste volume	Made use of rate reserve funds (FL)
		Opened services to more municipalities (FL)
	Shortage of waste collection personnel due to illness and quarantining	Suspended curbside recycling (FL)
		Delayed waste pickup (FL, CA)
		Increased waste collection operational hours (FL)
		Used trained emergency waste truck drivers (FL)
	Increase in residential waste volume	Made adjustments to waste collection routes and allocation of staff (FL, CA, NY)
		Increased waste collection operational hours (FL, CA, NY)
		Moved staff from yard waste collection services to residential waste collection (FL)
		Shifted resources from commercial waste to residential waste collection (FL, CA)
		Delayed waste pickup services (FL, NY)
		Allowed customers to drop off yard waste at landfills (NY)
	Increase in self-haul services	Trained more staff (FL)
	Increase in yard waste	Notified customers to cut down on yard work (FL)
		Allowed customers to drop off yard waste at landfills (FL)
		Provided options to use residential curbside yard waste collection instead of drop-off facilities (FL)
		Required customers to place all items in the trunk of vehicles to limit face-to-face contact (FL)
		Suspended yard waste collection temporarily (FL)

FL: Florida, CA: California, and NY: New York.

4.2. Waste Recycling

Similar to the investigated waste collection challenges, all recycling challenges affecting MSWMSs were reported during the first quarter of the study period, as depicted in Figure 4. The increase in recycling contamination was the only challenge that persisted during the entire timeline of the study. Systems that faced this challenge experienced an increase in the contamination of recyclables ranging between 9% to 11%. The fear about the transmission of the virus via surface contact impacted both policies and the public's mindset on recycling. For instance, news media stated that New York's MSWMSs saw an increase in tonnages and contamination in their recycling waste stream due to the suspension of reusable grocery bags and relaxed bottle bill enforcement, thus placing unacceptable materials (e.g., expanded polystyrene foam and single-use plastic) into the recycling stream. Meanwhile in California and Florida's MSWMSs, the observed increase in recycling contamination was mainly due to the influence of the virus on the public's recycling practices. For example, one system in Florida experienced an increase in the amount of unacceptable materials (e.g., used masks and gloves) going into the recycling stream, as residents were not sure how to dispose of this new kind of waste.

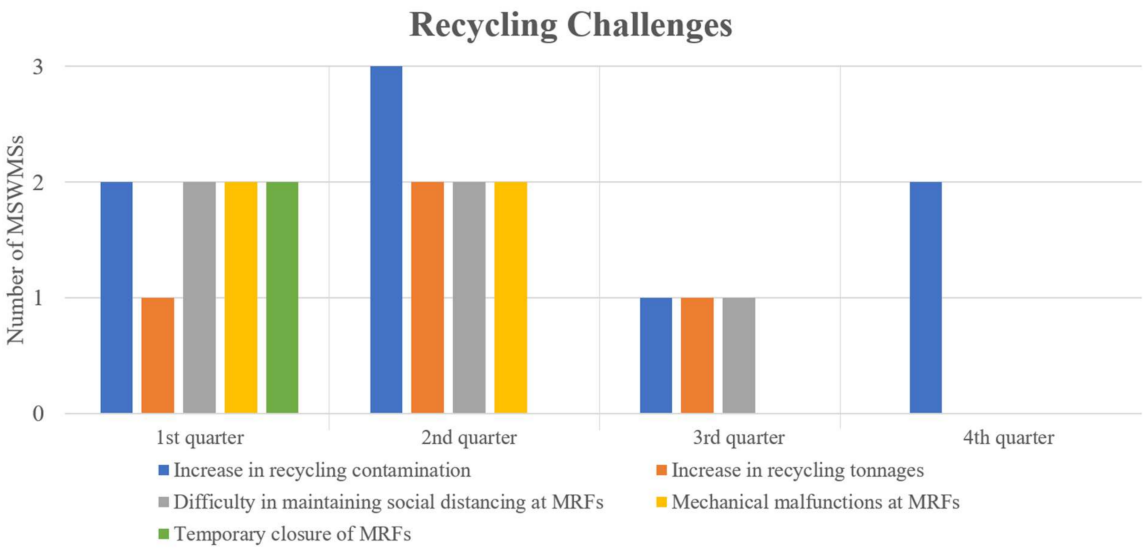

Figure 4. Recycling challenges affecting MSWMSs throughout the study timeline.

Another significant recycling challenge that was faced by MSWMSs in all three states is the increase in recycling tonnages. The factors contributing to this challenge varied with the progression of time and the evolution of the pandemic. During the first quarter, the increase in recycling tonnages was faced by one system only, and it was mainly due to the increase in the use of single-use plastic. Meanwhile, during the second quarter, the systems that saw an increase in recycling tonnages were the ones that had to temporarily close their recycling facilities during the first quarter. As for the last quarter during which this challenge was reported (i.e., third), the only persisting factor contributing to the increase in recyclables was customers still working from home, ordering deliveries and take-outs, and doing their shopping online, thereby producing more paper, cardboard, and plastic waste. According to the recycling composition studies conducted by systems which experienced an increase in recycling tonnages, the increase in the percentage of newspapers in the recycling stream ranged between 3% to 21%; similarly, such increase ranged between 2% and 7% for glass, and between 3% and 8% for corrugated cardboard.

Regional and international pandemic-related factors have also caused recycling-related challenges. During the first two quarters of the study period, two of Florida's MSWMSs encountered mechanical malfunctions at their material recovery facilities (MRFs). From the monthly interviews and news media content analysis, it was discovered that the pandemic-caused travel restrictions hindered the availability of professionals to do mechanical repairs at the recycling facilities.

As the primary causes of the challenges vary across states, so do the adaptive strategies taken by each MSWMS. In response to the increase in recycling contamination which can place waste handlers at a high risk of being exposed to the virus, Florida's MSWMSs opted to temporarily suspend recycling services and divert this waste stream to waste incineration facilities, if available, or landfills. Further, in an attempt to solve the root cause of the recycling contamination challenge, Florida's MSWMSs launched recycling educational awareness campaigns that aim to educate the public on proper recycling practices and to increase their awareness on the need to do so. This was done through online educational presentations and listings of acceptable recyclable materials on the systems' websites. In response to the same challenge of the increase in recycling contamination, California's and New York's participating MSWMSs took different mitigation approaches, predominantly because recycling and composting represent their main waste management services. California's MSWMSs opted to keep treating recyclables at MRFs; yet, they enacted a new measure of delaying the sorting of recyclables for up to three days in an effort to minimize workers' exposure to the virus. As for New York's MSWMSs, they

enforced a fine for improper recycling practices to curb the increasing contamination of the recyclable waste stream. The fact that these systems own and operate the MRFs increased the feasibility of implementing such mitigation measures. All other adaptive measures taken in response to the previously identified recycling challenges are provided in Table 2.

Table 2. Summary of all adaptation strategies taken for each waste recycling challenge.

Challenge Category	Challenge Subcategory	Adaptive Measures (States)
Recycling Challenges	Limited availability of professionals to repair mechanical malfunctions at MRFs	Diverted more recyclables to landfills (FL)
		Diverted residential recyclables to WTE facilities (FL)
		Suspended curbside recycling collection (FL)
	Increase in recycling contamination	Launched online educational awareness campaigns on the need to recycle properly (FL)
		Increased recycling operational costs (FL)
		Diverted recyclables to WTE facilities (FL)
		Delayed the sorting of recyclables for up to three days from the time of their collection (CA)
		Enforced a fine for improper recycling practices (NY)
	Increase in recycling tonnages	Increased the operational hours of MRFs (FL)
		Suspended curbside recycling collection temporarily (CA)
		Temporarily banned plastics within the facility (NY)
	Temporary closure of MRFs	-
	Difficulty in maintaining social distancing at MRFs	-

FL: Florida, CA: California, and NY: New York.

4.3. Health Challenges

Three main challenges were identified in this study under the health category: (i) concerns about workers' exposure to the virus, (ii) difficulty in maintaining social distancing in waste management facilities, and (iii) shortage of personal protective equipment, as presented in Figure 5. Since all three challenges are related to the infectious nature of COVID-19, they were experienced by each participating MSWMS, as reported in the monthly interviews, and as inferred from the news media content analysis. The concern about workers' exposure to the virus was the challenge that persisted during the entirety of the study period. As each state started reopening during the second quarter, spikes in COVID-19 cases were reported, which increased the concern about MSWMSs' staff becoming sick. Specifically, waste management personnel who had to have direct interactions with customers were the primary concern of waste management decision-makers. During the last two quarters, the frequency of reporting this challenge decreased as systems implemented appropriate adaptive measures. Further, difficulty in maintaining social distancing at waste management facilities is the second most recurring health challenge. Seven out of nine systems reported this challenge during the first two quarters, while three systems reported this challenge during the third quarter. Participating MSWMSs that were the most concerned about maintaining social distancing in their facilities were the ones reporting that their facilities have limited space, which can be insufficient to allow social distancing of staff. As for the shortage of PPE, it was the one challenge that was only reported during the first two quarters of the study period. While participating systems in Florida and New York reported challenges in acquiring PPE due to high public demand, California's MSWMSs did not experience such difficulty since they already had protective masks in stock due to the state being prone to wildfires.

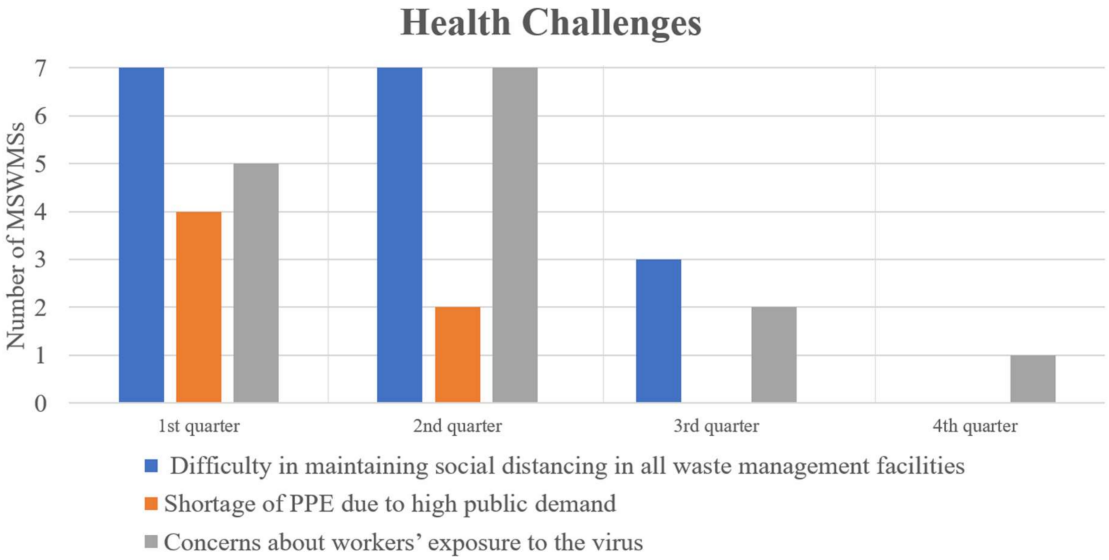

Figure 5. Health challenges affecting MSWMSs throughout the study timeline.

Studied MSWMSs employed various adaptive measures to respond to health-related challenges (Table 3). For example, MSWMSs in all three states suspended paper handling and removed access requirements for customers visiting administrative buildings in an effort to resolve the challenges related to social distancing within facilities. Further, Florida and New York systems implemented more rigorous measures by constructing ticket booths and installing plexiglass barriers between staff and customers. These measures were initially considered temporary, but they were later deemed to be adopted as a common practice even after the end of the pandemic. As for the concern about workers' exposure to the virus, all three states enforced the use of PPE, conducted daily virus screening activities, and sanitized areas frequently. News media content analysis showed that many systems consistently implemented these adaptive measures throughout the data collection period. In addition to these measures, Florida's systems reported giving non-essential employees paid administrative leave during the first two quarters and enforced the COVID-19 vaccination in the last quarter.

4.4. Business Continuity Challenges

With regards to challenges related to business continuity, the major challenge that was reported during all four quarters of the study period was the decrease in waste collection revenues (Figure 6). This challenge can be mainly attributed to the significant changes in the generation rates of different waste streams (e.g., a decrease in commercial waste), the cancellation or temporary suspension of some collection services, and the shrinkage of services in the business sector. According to the results of news media content analysis pertaining to one of the studied MSWMSs in New York, another reason behind this challenge may be the temporary diversion of services and resources to other sectors.

Another identified business continuity-related challenge was the increase in trash collection costs. Both the monthly interviews and the news media content analysis indicated that this challenge was mainly due to the increase in residential waste volume, which mandated increasing both the operational hours and the frequency of waste hauling services in order to meet the higher demand for residential waste collection. Although all three states experienced an increase in residential waste volume during the study timeline, only Florida and California MSWMSs reported facing the challenge of an increase in trash collection costs. As for the costs of recycling operations, only one MSWMS in Florida reported facing an increase in said costs, specifically during the third quarter of the

study period. The monthly interviews showed that this challenge was mainly due to the experienced increase in recycling contamination.

Table 3. Summary of all adaptation strategies taken for each health challenge.

Challenge Category	Challenge Subcategory	Adaptive Measures (States)
Health Challenges	Difficulty in maintaining social distancing in all waste management facilities	Constructed ticket booths and installed plexiglass barriers (FL, NY)
		Created separate areas for drivers and staff (FL)
		Closed household hazardous waste collection center to customers (FL)
		Divided staff into groups and assigned them staggered workdays (FL)
		Organized weekly safety meetings (FL)
		Restricted public activities and visitors' access to waste management facilities (FL)
		Suspended paper handling and removed access requirements for customers (FL, CA, NY)
		Suspended cash transactions at facilities, compost pickup by customers, and other types of operations with primary customer contact (FL,NY)
	Concerns about workers' exposure to the virus	Conducted daily COVID-19 screening (FL, CA, NY)
		Enforced COVID-19 vaccination (FL)
		Mandated use of masks (FL, CA, NY)
		Gave non-essential employees a paid administrative leave (FL)
		Required customers to place all items in the trunk of their vehicles to limit face-to-face contact (FL)
		Sanitized areas frequently (FL, CA, NY)
		Spaced employees apart to maintain social distancing (FL,CA)
		Trained more staff to fill in for quarantined employees (FL, NY)
		Shifted to remote work for all administrative staff and closed administrative buildings to the public (FL, CA, NY)
	Shortage of PPE due to high public demand	Increased operational budget to supply PPE to employees (FL, NY)
		Obtained PPE from other sources (FL)

FL: Florida, CA: California, and NY: New York.

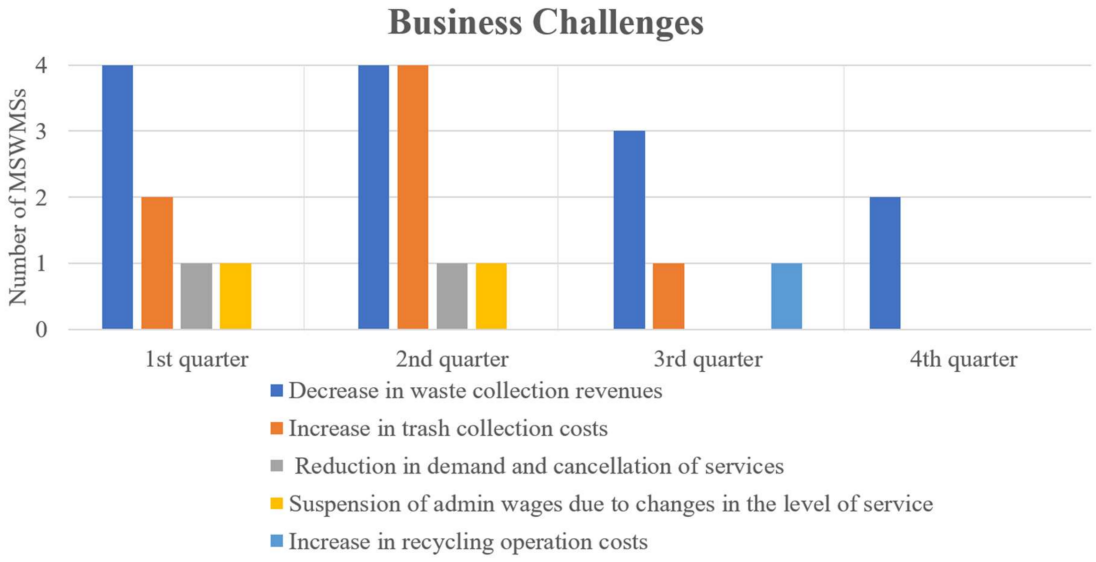

Figure 6. Business continuity challenges affecting MSWMSs throughout the study timeline.

Even though all three states experienced a decrease in waste collection revenues, only participating MSWMSs in Florida and California opted to implement adaptive measures to address this challenge. Systems in both states planned and approved an increase in the residential solid waste impact fees in an effort to offset the decrease in waste collection revenues from the commercial side. As for the reported challenge of an increase in trash collection costs, the sole affected system in Florida responded by adopting a range of adaptation strategies, such as covering redistribution of resources, modifications to imposed fees and utilization of funds, and changes to contracting practices (Table 4).

Table 4. Summary of all adaptation strategies taken for each business continuity challenge.

Challenge Category	Challenge Subcategory	Adaptive Measures (States)
Business Continuity Challenges	Decrease in waste collection revenues	Increased residential solid waste impact fee (FL, CA)
		Planned an increase in rates for next fiscal year's annual residential waste fee (FL, CA)
		Reduced operational hours (FL, CA)
	Reduction in demand and cancelation of services	Reduced operational hours (FL)
	Increase in trash collection costs	Approved an extension of contracts with the waste haulers (FL)
		Increased residential solid waste impact fee (FL)
		Provided options to renegotiate contracts or reduce the level of service (FL)
		Shifted resources from commercial waste collection to residential waste collection (FL)
		Used rate stabilization funds to offset future growth in operation and collection costs (FL)
		Used residential revenues to offset the decline in commercial waste and other MSW revenues (FL)
	Suspension of admin wages due to changes in the level of service	-
	Increase in recycling operation costs	-

FL: Florida, CA: California, and NY: New York.

Not all identified challenges related to the business continuity of MSWMSs were responded to or mitigated. With regards to the reported suspension of admin wages due to changes in the level of service and the increase in recycling operation costs, no adaptive measures were taken by the affected MSWMSs.

4.5. Waste Landfilling

In terms of challenges related to waste landfilling, none of the participating MSWMSs in the state of New York seems to have faced any, based on both the monthly reviews and the news media content analysis. As for the participating MSWMSs in Florida and California, they reported two main waste landfilling challenges during the first three quarters of the study period: an increase in demand for waste landfilling and difficulty in maintaining social distancing at the landfills (Figure 7). Between the two, the increase in demand for waste landfilling was more severe, as it was reported more frequently across different MSWMSs. Based on the information collected from the monthly interviews, it was inferred that due to the increase in waste volume and delay of waste collection services, many small businesses and residential customers needed to dispose of their waste directly at the landfill. One MSWMS in Florida reported that this increase in demand created traffic congestion within their facilities, subsequently delaying waste disposal services. As for the reported difficulty in maintaining social distancing at the landfill, it was experienced by MSWMSs

which were specifically concerned about staff at the scale houses being exposed to the virus due to the limited available space at the facilities, impeding proper social distancing.

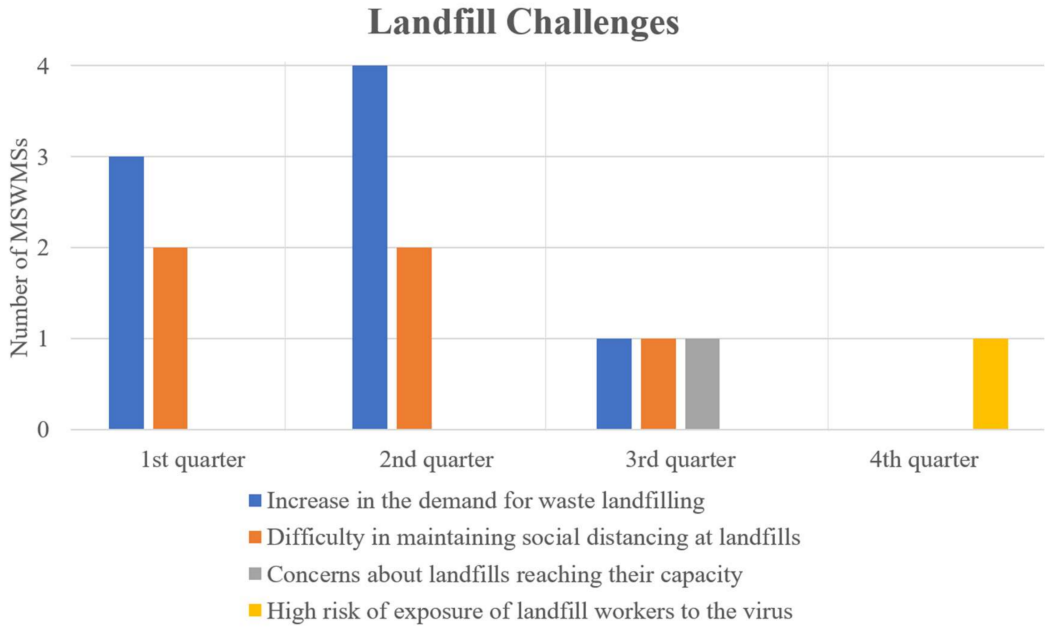

Figure 7. Waste landfilling challenges affecting MSWMSs throughout the study timeline.

Another waste landfilling-related challenge, faced by only one MSWMS, emerged only during the third quarter of the study period. Specifically, one MSWMS in Florida reported having concerns about its landfill reaching its capacity. Results of the news media content analysis showed that this was mainly due to the experienced increase in residential and yard waste, along with the bulky items, entering the landfill. If the capacity of a landfill is reached, no more waste can be disposed of in that landfill, which could be a major issue for the impacted MSWMS as landfills are often the most common places for waste disposal.

Table 5 summarizes all adaptation measures taken in response to the identified waste landfilling challenges. Although these challenges were reported in both California and Florida, almost all of the identified adaptive measures were implemented by MSWMSs in Florida. The only adaptive measure implemented in both states was increasing the working phase size in response to the rise in demand for waste landfilling. To cope with the same challenge, Florida MSWMSs further suspended compost pickup by customers in order to focus on satisfying the increasing need for waste disposal, as well as to minimize customers coming to landfill facilities.

Table 5. Summary of all adaptation strategies taken for each waste landfilling challenge.

Challenge Category	Challenge Subcategory	Adaptive Measures (States)
Landfill Challenges	Concerns about landfills reaching their capacity	Approved plans to increase landfills' capacity (FL)
	High risk of exposure of landfill workers to the virus	Contracted additional staff (FL)
		Trained staff to fill in for quarantined employees (FL)
	Difficulty in maintaining social distancing at landfills	Enforced the use of PPE (FL)
		Restricted public activities and visitors' access to landfills (FL)
	Increase in the demand for waste landfilling	Increased the size of the working phase (FL,CA)
		Suspended compost pickup by customers (FL)

FL: Florida, CA: California, and NY: New York.

4.6. Waste Incineration

Two main challenges impacting waste incineration were identified throughout the study period: difficulty in maintaining social distancing at WTE facilities and the limited availability of professionals to repair mechanical malfunctions at these facilities (Figure 8). All participating MSWMSs in Florida having WTE facilities faced either one or both of these challenges. Between the two identified challenges, the difficulty in maintaining social distancing at WTE facilities persisted throughout the first three quarters of the study period. Due to the increase in the volume of waste coming into the WTE facilities, the need for the full presence of all staff working at these facilities increased. This, however, resulted in difficulties in maintaining proper social distancing. All impacted systems reported creating separate areas for drivers and staff within their WTE facilities, along with restricting customers' access to the facilities. As for the challenge of repairing mechanical malfunctions at the WTE facilities amidst the limited availability of professionals, one MSWMS in Florida was impacted by this challenge during the beginning of the pandemic. This can be mainly attributed to the imposed travel restrictions during that period, which forced the affected WTE facilities to minimize their quarterly maintenance outage.

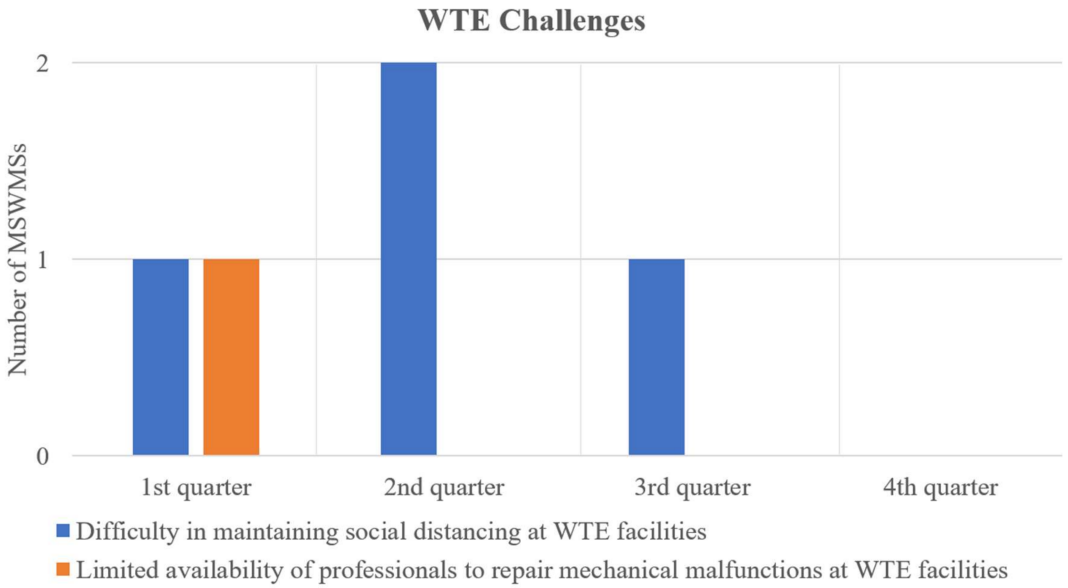

Figure 8. WTE challenges affecting MSWMSs throughout the study timeline.

4.7. C&D Waste Management

As more residential customers decided to do home renovations and clean-ups as a result of staying at home during the pandemic, some of the participating MSWMSs reported an increase in the amount of bulky items such as furniture disposed of as C&D waste. Due to the increase in the volume of this waste stream, the need for more staff in C&D waste management facilities increased. Even though at least one MSWMS in each state has a C&D waste collection or treatment facility, only the three MSWMSs in Florida experienced difficulties in maintaining social distancing at their facilities. Figure 9 shows the trend of this challenge throughout the study period. The main adaptive measure taken by all MSWMSs experiencing this challenge was PPE enforcement for all workers inside the C&D waste management facilities at all times.

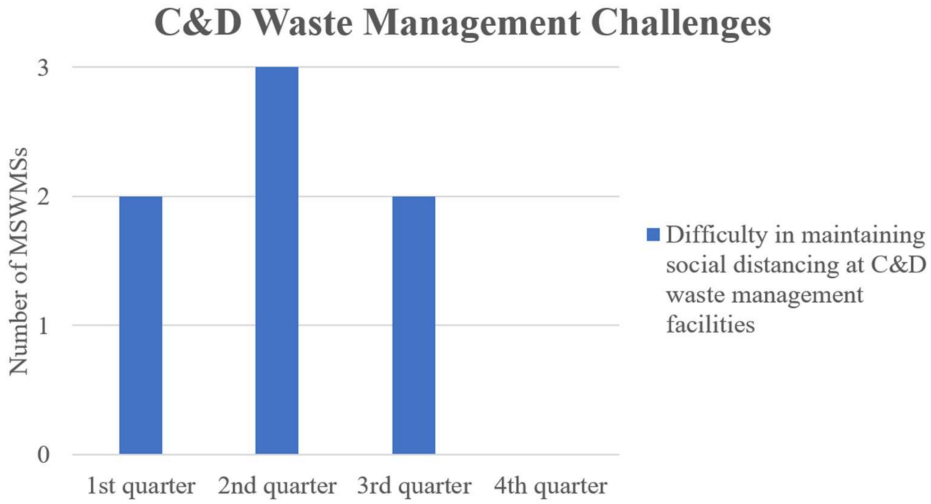

Figure 9. C&D waste management challenges affecting MSWMSs throughout the study timeline.

5. Development of a Pandemic-Specific MSWMSs Informational Database

Documenting the conducted investigation of the longitudinal impact of the coronavirus pandemic on MSWMSs is key to preserving significant findings and enabling data-based decision-making. Towards this end, this study develops an informational database that enables systematic recording and monitoring of the pandemic's impact on MSWMSs, as well as guides the implementation of different adaptation strategies based on distinct systems' characteristics. The informational database consists of 13 relational tables along with their specific attributes. Figure 10 depicts the table-relationship model constructed in Microsoft Access.

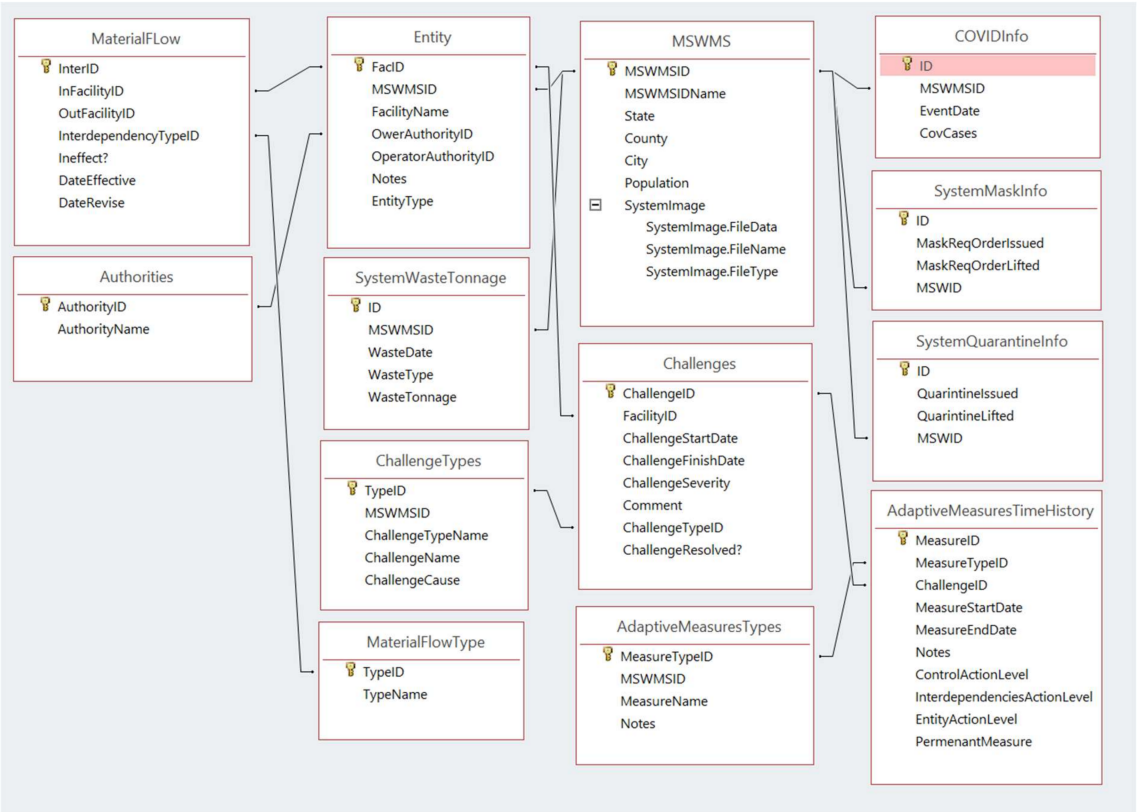

Figure 10. Table-relationship model of the informational database constructed in Microsoft Access.

The tables included in the database can be categorized into four groups: (1) entities and authorities, (2) waste information, (3) challenges, (4) adaptive measures, and (5) COVID-19 information. The entities and authorities group records information about each MSWMS component (e.g., location, size of the population served, entities, ownership, and operators). The waste information group records waste and waste flow (i.e., quantity and composition) time history among MSWMSs' entities. The challenges MSWMSs face during the COVID-19 pandemic, including their type, severity, and the entity facing each challenge, are recorded in the challenges group. The adaptive measures group records information regarding the type and category of adaptive measures devised by MSWMSs' authorities to respond to challenges and mitigate their impact. The COVID-19 information group captures the daily number of confirmed COVID-19 cases at the county level of each MSWMS, the period of system quarantine, and the period of the mask mandate. This information is useful to monitor the community's spread and its impact on the state of the MSWMSs.

As described, the database stores comprehensive operational, managerial, and contextual information with respect to each MSWMS, providing a well-managed knowledge platform that practitioners can use to share their experiences in managing MSW during the pandemic. Such a database augments the current limited understanding of the impact of the pandemic on MSWMSs. It also facilitates a more effective and efficient response and adaptation by allowing decision-makers, including those who have not participated in populating the data, to gain insights into how MSWMSs with similar characteristics have addressed challenges during the pandemic. The proposed structure of the database supports such filtering for integrated and consistent data aggregation. For instance, in the case of the recyclable waste contamination challenge, practitioners from systems with similar attributes to Florida MSWMSs can review how these systems have handled the disruption.

6. Discussion

6.1. Differential Impacts of Challenges on Post-Pandemic MSWMSs

Although existing literature discusses some of the main challenges that the COVID-19 pandemic imposed on MSWMSs, available studies do not investigate if these challenges remained significant throughout the pandemic timeline. For example, Tripathi et al. [29] reported that a surge in household waste was observed as a result of the pandemic, amid school closures, lockdown measures, and shifting to working from home. Although the results presented in this paper confirmed that the challenge of increased residential waste volume was reported during all four quarters, they also showed that the number of MSWMSs experiencing this challenge dropped from nine during the first quarter to only three during the fourth quarter of the study period. Similarly, Liang et al. [31] reported that a drop in commercial waste generation has been observed in highly touristic and commercial regions due to travel restrictions and closures of restaurants and businesses. However, the commercial waste volume decrease was only reported during the first and second quarters of the pandemic based on the results of this study. Further, many studies [28,36] identified manpower shortages due to the increase in rates of infections, staffing gaps, and quarantine measures as another significant challenge MSWMSs faced during the pandemic. Monthly interviews and content analysis results in this study, however, revealed that although many systems experienced difficulties in maintaining social distancing or acquiring PPE in the first three quarters of the pandemic, no system reported these challenges as the pandemic progressed during the fourth quarter of the study period. Based on the longitudinal investigation performed in this study, it can be inferred that some of the aforementioned challenges (e.g., increase in residential waste, decrease in commercial waste, and workforce issues) were more significant during the beginning of the pandemic, resulting in a short-term impact on MSWMSs.

6.2. Feasibility of Mitigation Strategies of MSWMSs and Their Adaptation during the Pandemic

Despite that a wide range of adaptive measures were proposed in the literature in response to the challenges posed by the COVID-19 pandemic, the feasibility of their im-

plementation differs in practice from one MSWMS to the other. For example, mitigation strategies proposed to respond to increased recyclable waste tonnages range from a complete halt of the recycling operations [36] to a normal recycling procedure [31]. However, due to differences in policies and availability of resources, the applicability of these strategies varies across different MSWMSs. In other words, decision-makers in each MSWMS need to select the most appropriate adaptive measure based on their regional context (e.g., policies, regulations, and community priorities) and system characteristics (e.g., the presence of facilities within a system). For example, in response to increased recyclable waste tonnages, Florida and California MSWMSs responded differently due to their different system characteristics. Florida systems opted to temporarily suspend their material recovery and redirect their waste to incineration facilities since WTE is their primary waste management approach. On the other hand, in California, recycling and composting operations remained ongoing, but with a newly enacted mitigation measure of delaying the sorting of recyclable waste for up to three days to protect waste management personnel.

Furthermore, based on the results of this study, it was also found that MSWMSs change and adapt their mitigation measures as their post-pandemic operations improve over time. For example, within the waste collection challenge category, an increase in yard waste volume was reported mainly during the first quarter of the study period. A number of systems chose to temporarily suspend yard waste collection as a drastic adaptation measure. However, as the initial impact of the pandemic was mitigated in the following quarters, these systems started to provide options for customers to drop off their yard waste at the landfill.

6.3. Significance of a Documented, Extensive, and Well-Maintained Knowledge Base

To date, existing knowledge in the context of resilient solid waste management systems is limited to the case of natural disasters. Such knowledge, however, is not applicable in the case of a novel pandemic event due to its unique waste demands and governing operational conditions. Further, as the results of this study revealed, MSWMSs experienced different challenges during the course of the pandemic. Even in response to a similar challenge, implemented adaptive measures varied across systems (i.e., depending on their regional contexts and system characteristics). With such variation in the nature of impact and possible response mechanisms, along with the current dearth of knowledge about the impact of a pandemic on solid waste management, there is a dire need for the development of a knowledge base documenting challenges faced by various MSWMSs during a pandemic, along with their adaptive processes. The informational database developed in this study can be used to effectively address such needs. Beyond the data collected in this study, the developed database can be expanded by encouraging more MSWMSs to share their experience and contribute to the database in a regular manner. This would diversify the types of participating systems and enrich the quality of information stored in the database, resulting in a more extensive and well-maintained knowledge base.

The described knowledge base has practical benefits that can be utilized both during and beyond the current pandemic. A number of published studies investigating the impact of the pandemic on solid waste management [4,25,26,28] have concluded that a pandemic-specific, long-term, and widespread data-based assessment is vital to systematically understand the unique dynamics of waste generated, along with identifying the characteristics of MSWMSs required for successful adaptation. Having a knowledge base, documented by means of a database, would serve as a fast and reliable source of all information needed to conduct the recommended assessment, particularly in terms of system-specific and time-bound challenges and adaptive measures. Beyond the current COVID-19 pandemic, the described knowledge base would also facilitate the development of emergency plans, and more proactive rather than reactive and ad hoc approaches for future pandemic scenarios. The knowledge stored in the proposed database can serve as documentation of the lessons learned during the COVID-19 pandemic. Such informa-

tion can be used to identify the most appropriate and effective methods, resources, and responses for distinct types of MSWMSs to help them prepare for future disruptive events.

7. Conclusions

The COVID-19 pandemic has brought unprecedented challenges to MSWMSs, covering a range of operational and managerial aspects. To successfully maintain a vital service, MSWMSs have adopted various adaptation and mitigation strategies in response to emerging demands and operational difficulties during the pandemic. While some research studies have been conducted to identify some of the waste management challenges faced during the pandemic and potential adaptation measures to be taken, none of these studies investigated how these challenges and adaptive measures vary with time and across MSWMSs. This study addresses the existing knowledge gap by performing a micro-level, time-bound investigation of the longitudinal impact of the pandemic on nine distinct MSWMSs across three U.S. states (i.e., Florida, California, and New York). Using three different data collection methods (i.e., monthly interviews, news media content analysis, and waste tonnage data analysis), the challenges faced by these MSWMSs and their implemented adaptive measures were studied. Some of the challenges that were found to be impacting MSWMSs throughout the study timeline across different states are (i) the increase in residential volume, (ii) decrease in waste collection revenues, (iii) shortage of waste collection personnel due to illness and quarantining, (iv) concern on workers' exposure to the virus, and (v) the increase in recycling contamination. The severity of these challenges, along with their adaptive measures, however, were found to vary depending on the system characteristics of the MSWMSs and their regional contexts.

The emerging and varying nature of the impact of the COVID-19 pandemic on MSWMSs, along with how they distinctly responded and adapted, highlighted the need for documenting such time-bound and system-specific information in a comprehensive knowledge base. Such need motivated the design and establishment of an informational database, capturing the post-pandemic information focusing on the challenges and adaptive measures of MSWMSs with varying system characteristics and regional factors. This initiative enables a better understanding of the repercussions of the current pandemic on MSWMSs, along with facilitating accelerated and more effective response and system adaptation. Further, the proposed documented knowledge base can serve as a guide in the development of plans for future pandemic scenarios towards more resilient MSWMSs.

Author Contributions: Conceptualization, J.C. and T.A.; methodology, J.C. and T.A.; validation, A.D.P., J.C. and T.A.; formal analysis, A.D.P., H.J. and F.S.; investigation, A.D.P. and F.S.; data curation, A.D.P., N.N., H.J. and F.S.; writing—original draft preparation, A.D.P., H.J. and N.N.; writing—review and editing, A.D.P., H.J., N.N., J.C. and T.A.; visualization, A.D.P., H.J. and N.N.; supervision, J.C. and T.A.; project administration, A.D.P., J.C. and T.A.; funding acquisition, J.C. and T.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the U.S. National Science Foundation under grant number CBET-2030254.

Institutional Review Board Statement: Ethical review and approval were waived for this study, since the information obtained is recorded in such a manner that human subjects cannot be identified, directly or through identifiers linked to the subject; or any disclosure (including accidental disclosure) of the human subjects' responses outside the research could not reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to privacy restrictions.

Acknowledgments: The authors also would like to acknowledge the support from the participating technical group members from all MSWMSs interviewed. Any opinions, findings, and conclusions or

recommendations expressed in this paper are those of the authors and do not necessarily reflect the view of the National Science Foundation.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. WHO. WHO Coronavirus (COVID-19) Dashboard. 2022. Available online: https://covid19.who.int/ (accessed on 15 January 2022).
2. Nabavi-Pelesaraei, A.; Mohammadkashi, N.; Naderloo, L.; Abbasi, M.; Chau, K. Principal of environmental life cycle assessment for medical waste during COVID-19 outbreak to support sustainable development goals. *Sci. Total Environ.* **2022**, *827*, 154416. [CrossRef] [PubMed]
3. Irfan, M.; Ahmad, M.; Fareed, Z.; Iqbal, N.; Sharif, A.; Wu, H. On the indirect environmental outcomes of COVID-19: Short-term revival with futuristic long-term implications. *Int. J. Environ. Health Res.* **2021**, 1–11. [CrossRef] [PubMed]
4. Roy, P.; Mohanty, A.K.; Wagner, A.; Sharif, S.; Khalil, H.; Misra, M. Impacts of COVID-19 outbreak on the municipal solid waste management: Now and beyond the pandemic. *ACS Environ. Au* **2021**, *1*, 32–45. [CrossRef]
5. Nabavi-Pelesaraei, A.; Bayat, R.; Hosseinzadeh-Bandbafha, H.; Afrasyabi, H.; Berrada, A. Prognostication of energy use and environmental impacts for recycle system of municipal solid waste management. *J. Clean. Prod.* **2017**, *154*, 602–613. [CrossRef]
6. UNEP. Waste Management an Essential Public Service in the Fight to Beat COVID-19. *United Nations Environment Programmet Programme*. 2020. Available online: https://www.unep.org/news-and-stories/press-release/waste-management-essential-public-service-fight-beat-covid-19 (accessed on 15 January 2022).
7. Mihai, F.C. Assessment of COVID-19 waste flows during the emergency state in romania and related public health and environmental concerns. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5439. [CrossRef]
8. Akash, S.; Sivaprakash, B.; Vadivel Raja, V.C.; Rajamohan, N.; Muthusamy, G. Remediation techniques for uranium removal from polluted environment-Review on methods, mechanism and toxicology. *Environ. Pollut.* **2022**, *302*, 119068. [CrossRef]
9. Pandiana, A.M.K.; Rajamehalaa, M.; Singh, M.V.P.; Sarojini, G.; Rajamohan, N. Potential risks and approaches to reduce the toxicity of disinfection by-product–A review. *Sci. Total Environ.* **2022**, *822*, 153323. [CrossRef]
10. Saravanan, P.; Rajeswari, S.; Kumar, J.A.; Rajasimman, M.; Rajamohan, N. Bibliometric analysis and recent trends on MXene research—A comprehensive review. *Chemosphere* **2022**, *286*, 131873. [CrossRef]
11. Nzeadibe, T.C.; Ejike-Alieji, A.U.P. Solid waste management during COVID-19 pandemic: Policy gaps and prospects for inclusive waste governance in Nigeria. *Local Environ.* **2020**, *25*, 527–535. [CrossRef]
12. Nabavi-Pelesaraei, A.; Bayat, R.; Hosseinzadeh-Bandbafha, H.; Afrasyabi, H.; Chau, K. wing Modeling of energy consumption and environmental life cycle assessment for incineration and landfill systems of municipal solid waste management—A case study in Tehran Metropolis of Iran. *J. Clean. Prod.* **2017**, *148*, 427–440. [CrossRef]
13. Commerce Ministry. Press Conference of the Joint Prevention and Control Mechanism of the State Council Information Office. Commerce, Ministry of China, People's Republic of URL. 2020. Available online: http://english.mofcom.gov.cn/article/newsrelease/press/202004/20200402956415.shtml (accessed on 2 January 2022).
14. Association of Directors of Environment Economy Planning and Transport. COVID 19—Waste Survey Results w/c 27 April, 2020. Available online: https://www.adeptnet.org.uk/documents/covid-19-waste-survey-results-wc-27-april-0 (accessed on 15 January 2022).
15. Solid Waste Association of North America (SWANA). SWANA Reminds All State and Local Governments That Solid Waste Management Is an Essential Public Service. 2020. Available online: https://swana.org/news/swana-news/article/2020/03/19/swana-reminds-all-state-and-local-governments-that-solid-waste-management-is-an-essential-public-service (accessed on 29 January 2021).
16. Waste Advantage. The Impact of COVID-19 on the Waste and Recycling Industry. 2020. Available online: https://wasteadvantagemag.com/the-impact-of-covid-19-on-the-waste-and-recycling-industry/ (accessed on 2 March 2021).
17. BIR. COVID-19: Update by BIR Member National Associations—The World Moves Tentatively into Reopening Phase. *Bureau of International Recycling*. 2020. Available online: https://bir.org/news-press/news/item/covid-19-update-by-bir-member-national-associations-the-world-moves-tentatively-into-reopening-phase (accessed on 2 October 2021).
18. Staub, C. City Data Shows COVID-19 Impacts on Recycling Tonnages. Resource Recycling. 2020. Available online: https://resource-recycling.com/recycling/2020/04/28/city-data-shows-covid-19-impacts-on-recycling-tonnages/ (accessed on 2 October 2020).
19. Staub, C. COVID-19 Damages Supply Chain for Deposit Materials. Resource Recycling. 2020. Available online: https://resource-recycling.com/recycling/2020/04/14/covid-19-damages-supply-chain-for-deposit-materials/ (accessed on 5 November 2020).
20. Kaufman, L.; Chasan, E. Cities Wonder Whether Recycling Counts as Essential During the Virus. Bloomberg Green. 2020. Available online: https://www.bloomberg.com/news/articles/2020-03-27/cities-wonder-whether-recycling-counts-as-essential-during-the-virus (accessed on 22 January 2021).

21. ACRPlus. Municipal Waste Management and COVID-19. Association of Cities and Regions for Sustainable Resource Managementanagement. 2020. Available online: https://www.acrplus.org/en/municipal-waste-management-covid-19#lebanon (accessed on 29 January 2021).
22. Land Oberosterreich. Corona Virus: Waste Disposal. The State of Upper Austria. 2020. Available online: https://www.land-oberoesterreich.gv.at/232676.htm (accessed on 2 December 2020).
23. Argento, M. Coronavirus Prompts Changes in Trash Collection. York Daily Record. 2020. Available online: https://www.ydr.com/story/news/2020/03/27/coronavirus-prompts-changes-trash-collection/2926389001/ (accessed on 2 September 2020).
24. Siming, Y.; Sonne, C.; Ok, Y.S. COVID-19's unsustainable waste management. *Science* **2020**, *368*, 1438.
25. Naughton, C.C. Will the COVID-19 pandemic change waste generation and composition?: The need for more real-time waste management data and systems thinking. *Resour. Conserv. Recycl.* **2020**, *162*, 105050. [CrossRef] [PubMed]
26. Sharma, H.B.; Vanapalli, K.R.; Cheela, V.S.; Ranjan, V.P.; Jaglan, A.K.; Dubey, B.; Goel, S.; Bhattacharya, J. Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic. *Resour. Conserv. Recycl.* **2020**, *162*, 105052. [CrossRef] [PubMed]
27. Sarkodie, S.; Owusu, P. Impact of COVID-19 pandemic on waste management. *Environ. Dev. Sustain.* **2020**, *23*, 7951–7960. [CrossRef]
28. Van Fan, Y.; Jiang, P.; Hemzal, M.; Klemeš, J.J. An update of COVID-19 influence on waste management. *Sci. Total Environ.* **2021**, *754*, 142014. [CrossRef]
29. Tripathi, A.; Tyagi, V.K.; Vivekanand, V.; Bose, P.; Suthar, S. Challenges, opportunities and progress in solid waste management during COVID-19 pandemic. *Case Stud. Chem. Environ. Eng.* **2020**, *2*, 100060. [CrossRef]
30. Hantoko, D.; Li, X.; Pariatamby, A.; Yoshikawa, K.; Horttanainen, M.; Yan, M. Challenges and practices on waste management and disposal during COVID-19 pandemic. *J. Environ. Manag.* **2021**, *286*, 112140. [CrossRef]
31. Liang, Y.; Song, Q.; Wu, N.; Li, J.; Zhong, Y.; Zeng, W. Repercussions of COVID-19 pandemic on solid waste generation and management strategies. *Front. Environ. Sci. Eng.* **2021**, *15*, 1–18. [CrossRef]
32. Singh, E.; Kumar, A.; Mishra, R.; Kumar, S. Solid waste management during COVID-19 pandemic: Recovery techniques and responses. *Chemosphere* **2022**, *288*, 132451. [CrossRef]
33. Kahlert, S.; Bening, C.R. Plastics recycling after the global pandemic: Resurgence or regression? *Resour. Conserv. Recycl.* **2020**, *160*, 104948. [CrossRef]
34. Kulkarni, B.N.; Anantharama, V. Repercussions of COVID-19 pandemic on municipal solid waste management: Challenges and opportunities. *Sci. Total Environ.* **2020**, *743*, 140693. [CrossRef] [PubMed]
35. Torkashvand, J.; Jonidi Jafari, A.; Godini, K.; Kazemi, Z.; Kazemi, Z.; Farzadkia, M. Municipal solid waste management during COVID-19 pandemic: A comparison between the current activities and guidelines. *J. Environ. Health Sci. Eng.* **2021**, *19*, 173–179. [CrossRef] [PubMed]
36. Yousefi, M.; Oskoei, V.; Jonidi Jafari, A.; Farzadkia, M.; Hasham Firooz, M.; Abdollahinejad, B.; Torkashvand, J. Municipal solid waste management during COVID-19 pandemic: Effects and repercussions. *Environ. Sci. Pollut. Res.* **2021**, *28*, 32200–32209. [CrossRef] [PubMed]
37. Busetto, L.; Wick, W.; Gumbinger, C. How to use and assess qualitative research methods. *Neurol. Res. Pract.* **2020**, *2*, 1–10. [CrossRef]
38. Roller, M.R.; Lavrakas, P.J. *Applied Qualitative Research Design: A Total Quality Framework Approach*; Guilford Publications: New York, NY, USA, 2015; ISBN 1462519083.
39. Evans, W. Computer-Supported Content Analysis. *Soc. Sci. Comput. Rev.* **1996**, *14*, 269–279. [CrossRef]
40. Landis, J.R.; Koch, G.G. The Measurement of Observer Agreement for Categorical Data. *Biometrics* **1977**, *33*, 159–174. [CrossRef]
41. Florida Department of Environmental Protection. Waste-to-Energy. 2017. Available online: https://floridadep.gov/waste/permitting-compliance-assistance/content/waste-energy (accessed on 15 March 2021).
42. California Assembly Bill-1857. California Legislative Information. 2022. Available online: https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB1857 (accessed on 1 February 2022).
43. New York State Department of Environmental Conservation. Recycling and Composting. 2021. Available online: https://www.dec.ny.gov/chemical/294.html (accessed on 1 August 2021).
44. Ballotpedia. Documenting Florida's Path to Recovery from the Coronavirus (COVID-19) Pandemic, 2020–2021. 2021. Available online: https://ballotpedia.org/Documenting_Florida%27s_path_to_recovery_from_the_coronavirus_(COVID-19)_pandemic,_2020-2021 (accessed on 1 August 2021).
45. Ballotpedia. Documenting California's Path to Recovery from the Coronavirus (COVID-19) Pandemic, 2020–2021. 2021. Available online: https://ballotpedia.org/Documenting_California%27s_path_to_recovery_from_the_coronavirus_(COVID-19)_pandemic,_2020-2021 (accessed on 15 September 2021).
46. Ballotpedia. Documenting New York's Path to Recovery from the Coronavirus (COVID-19) Pandemic, 2020–2021. 2021. Available online: https://ballotpedia.org/Documenting_New_York%27s_path_to_recovery_from_the_coronavirus_(COVID-19)_pandemic,_2020-2021 (accessed on 20 August 2021).
47. McCormick, E. 'It's All on Hold': How COVID-19 Derailed the Fight against Plastic Waste. The Guardian. 2020. Available online: https://www.theguardian.com/environment/2020/jul/09/covid-19-plastic-bans-california-new-york (accessed on 1 November 2020).
48. New York State Department of Environmental Conservation. COVID-19 and Bottle Bill Beverage Container Redemption. 2020. Available online: https://www.dec.ny.gov/chemical/119925.html (accessed on 5 October 2020).